

# Implications of the VHE Gamma-Ray Detection of the Quasar 3C279

M. Böttcher<sup>1</sup>

and

A. Reimer<sup>2</sup>

and

A. P. Marscher<sup>3</sup>

## ABSTRACT

The MAGIC very-high-energy (VHE)  $\gamma$ -ray astronomy collaboration recently reported the detection of the quasar 3C279 at  $> 100$  GeV  $\gamma$ -ray energies. Here we present simultaneous optical (BVRI) and X-ray (*RXTE PCA*) data from the day of the VHE detection and discuss the implications of the snap-shot spectral energy distribution for jet models of blazars. A one-zone synchrotron-self-Compton origin of the entire SED, including the VHE  $\gamma$ -ray emission is highly problematic as it would require an unrealistically low magnetic field. The measured level of VHE emission could, in principle, be interpreted as Compton upscattering of external radiation (e.g., from the broad-line regions). However, such an interpretation would require either an unusually low magnetic field of  $B \sim 0.03$  G, or (in order to achieve approximate equipartition between magnetic field at  $B \sim 0.25$  G and relativistic electrons) an unrealistically high Doppler factor of  $\Gamma \sim 140$ . In addition, such a model fails to reproduce the observed X-ray flux. Furthermore, both versions of leptonic one-zone models produce intrinsic VHE  $\gamma$ -ray spectra steeper than measured, even in the case of the lowest plausible extragalactic  $\gamma\gamma$

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<sup>1</sup>Astrophysical Institute, Department of Physics and Astronomy,  
Clippinger 339, Ohio University, Athens, OH 45701, USA

<sup>2</sup>Stanford University, HEPL/KIPAC, Stanford, CA 94305, USA

<sup>3</sup>Institute of Astrophysical Research, Boston University,  
725 Commonwealth Avenue, Boston, MA 02215, USA

absorption. We therefore conclude that a simple one-zone, homogeneous leptonic jet model is not able to plausibly reproduce the SED of 3C279 including the recently detected VHE  $\gamma$ -ray emission. This as well as the lack of correlated variability in the optical with the VHE  $\gamma$ -ray emission and the substantial  $\gamma\gamma$  opacity of the BLR radiation field to VHE  $\gamma$ -rays suggests a multi-zone model in which the optical emission is produced in a different region than the VHE  $\gamma$ -ray emission. In particular, an SSC model with an emission region far outside the BLR reproduces the simultaneous X-ray — VHE  $\gamma$ -ray spectrum of 3C279. Alternatively, a hadronic model is capable of reproducing the observed SED of 3C279 reasonably well, both in scenarios in which only the internal synchrotron field serves as targets for  $p\gamma$  pion production, and with a substantial contribution from external photons, e.g., from the BLR. However, either version of the hadronic model requires a rather extreme jet power of up to  $L_j \sim 10^{49}$  erg s<sup>-1</sup>, compared to a requirement of  $L_j \sim 2 \times 10^{47}$  erg s<sup>-1</sup> for a multi-zone leptonic model.

*Subject headings:* galaxies: active — Quasars: individual (3C 279) — gamma-rays: theory — radiation mechanisms: non-thermal

## 1. Introduction

Flat-spectrum radio quasars (FSRQs) and BL Lac objects are active galactic nuclei (AGNs) commonly unified in the class of blazars. They exhibit some of the most violent high-energy phenomena observed in AGNs to date. Their spectral energy distributions (SEDs) are characterized by non-thermal continuum spectra with a broad low-frequency component in the radio – UV or X-ray frequency range and a high-frequency component from X-rays to  $\gamma$ -rays. In the framework of relativistic jet models, the low-frequency (radio – optical/UV) emission from blazars is interpreted as synchrotron emission from nonthermal electrons in a relativistic jet. The high-frequency (X-ray –  $\gamma$ -ray) emission could either be produced via Compton upscattering of low frequency radiation by the same electrons responsible for the synchrotron emission (leptonic jet models; for a recent review see, e.g., Böttcher 2007a), or due to hadronic processes initiated by relativistic protons co-accelerated with the electrons (hadronic models, for a recent discussion see, e.g., Mücke & Protheroe 2001; Mücke et al. 2003).

The quasar 3C279 ( $z = 0.536$ ) is one of the best-observed flat spectrum radio quasars, in part because of its prominent  $\gamma$ -ray flare shortly after the launch of the *Compton Gamma-Ray Observatory (CGRO)* in 1991. It was persistently detected by the *Energetic Gamma-ray*

*Experiment Telescope (EGRET)* on board *CGRO* each time it was observed, even in its very low quiescent states, e.g., in the winter of 1992 – 1993, and is known to vary in  $\gamma$ -ray flux by roughly two orders of magnitude (Maraschi et al. 1994; Wehrle et al. 1998). It has been monitored intensively at radio, optical, and more recently also X-ray frequencies, and has been the subject of intensive multiwavelength campaigns (e.g., Maraschi et al. 1994; Hartman et al. 1996; Wehrle et al. 1998). Observations with the *International Ultraviolet Explorer* in the very low activity state of the source in December 1992 – January 1993 revealed the existence of a thermal emission component, possibly related to an accretion disk (Pian et al. 1999).

A complete compilation and modeling of all available SEDs simultaneous with the 11 *EGRET* observing epochs has been presented in Hartman et al. (2001a). The modeling was done using the time-dependent leptonic synchrotron self-Compton (SSC) + External Compton (EC) model of Böttcher, Mause, & Schlickeiser (1997); Böttcher & Bloom (2000) and yielded quite satisfactory fits for all epochs. The results were consistent with other model fitting works (e.g., Bednarek 1998; Sikora et al. 2001; Moderski et al. 2003) concluding that the X-ray – soft  $\gamma$ -ray portion of the SED might be dominated by SSC emission, while the *EGRET* emission might require an additional component, most likely external-Compton emission.

During a recent observing campaign by the Whole Earth Blazar Telescope (WEBT) collaboration (Böttcher et al. 2007b) in the spring of 2006, intensive monitoring by the Major Atmospheric Gamma-Ray Imaging Cherenkov Telescope (MAGIC) yielded a positive detection at  $> 100$  GeV on February 23, 2006 (Albert et al. 2008). This makes 3C279 the first quasar and (as of April 2009) the most distant object detected in VHE  $\gamma$ -rays. In this paper, we present the optical (BVRI) and X-ray (*RXTE*) data taken simultaneously with the MAGIC detection, and discuss the implications of this detection for current standard blazar jet models.

Throughout this paper, we refer to  $\alpha$  as the energy spectral index,  $F_\nu$  [Jy]  $\propto \nu^{-\alpha}$ . A cosmology with  $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$ , and  $H_0 = 70$  km s $^{-1}$  Mpc $^{-1}$  is used. In this cosmology the luminosity distance of 3C 279 at a redshift of  $z = 0.536$  is  $d_L = 3.08$  Gpc.

## 2. Observations and results

3C 279 was observed in a WEBT campaign at radio, near-IR, and optical frequencies, throughout the spring of 2006. Details of the observations, data analysis, and implications of the optical variability patterns observed during that campaign have been published in

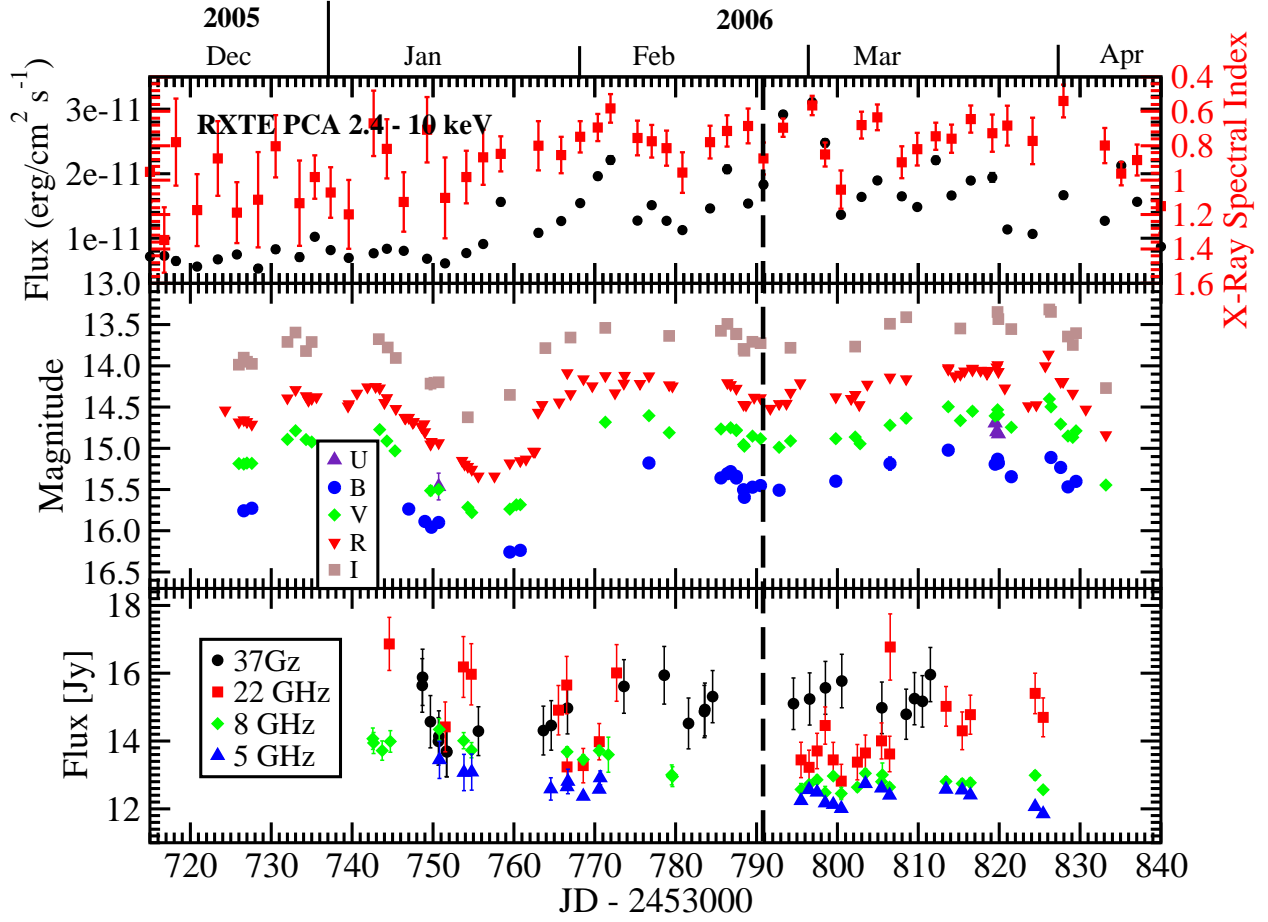


Fig. 1.— Light curves at radio (bottom), optical (center), and X-ray frequencies over the course of the WEBT campaign in the spring of 2006. The red points (right axis labels) indicate the energy spectral index in the 2 – 10 keV range. The vertical dashed line marks the day of the MAGIC VHE  $\gamma$ -ray detection.

Böttcher et al. (2007b). The source was simultaneously monitored with 3 pointings per week with the *Rossi X-ray Timing Explorer (RXTE)* Proportional Counter Array (PCA). We obtained the X-ray flux measurements with the PCA detector PCU2, using typical exposure times of 2 ks for each pointing. The data reduction is described in Chatterjee et al. (2008).

Fig. 1 shows the radio, optical and X-ray light curves of 3C279 during spring 2006, along with the 2 – 10 keV energy spectral index as a function of time. The dashed vertical line marks the day of the MAGIC > 100 GeV  $\gamma$ -ray detection. While the source was overall in an extended optical high state ( $R \sim 14.5$ ), no extraordinary variability in any optical (BVRI) band was observed at the time of the MAGIC detection.

During most of December 2005 and January 2006, the X-ray flux of 3C279 was in a low state, near its historical minimum. Around Jan. 25, however, the source made a transition to a higher X-ray flux state with substantial variability in flux and spectral index on a characteristic time scale of  $\sim 10$  days. The average flux increased to about a factor  $\sim 2 - 3$  compared to the low state. In the high state, there is a clear correlation between X-ray flux and spectral hardness, with the spectrum becoming harder as the flux increases. Statistical uncertainties preclude any conclusions about a flux-hardness correlation in the low X-ray state. The VHE flare observed by MAGIC precedes an X-ray outburst with the highest X-ray flux measured since the major optical/X-ray outburst in 2001 (see, e.g. Chatterjee et al. 2008), by  $\sim 5 - 7$  days.

Fig. 2 compares several historical SEDs of 3C279 to the one measured on February 23, 2006, along with the MAGIC VHE detection. The X-ray flux is comparable to the one observed during the major EGRET-detected  $\gamma$ -ray outburst in June 1991. The MAGIC data points show the measured flux, corrected for intergalactic  $\gamma\gamma$  absorption, using the lowest plausible level of extragalactic background light (EBL) cosmic infrared light, according to the model of Primack et al. (2005). As discussed in Albert et al. (2008), this yields a best-fit energy index to the corrected VHE spectrum of  $\alpha_{\text{VHE}} = 1.9 \pm 0.9_{\text{stat}} \pm 0.5_{\text{syst}}$ . Other currently discussed EBL models would predict a higher intrinsic VHE  $\gamma$ -ray flux and substantially harder spectrum. In particular, a high-EBL model (Stecker, Malkan, & Scully 2006) would lead to an intrinsic VHE spectral index of  $\alpha_{\text{VHE}} = -0.5 \pm 1.2_{\text{stat}} \pm 0.5_{\text{syst}}$ . As we will discuss below, the VHE spectrum corrected with the Primack et al. (2005) model already poses severe constraints on currently discussed blazar models. Those constraints would be even more restrictive and problematic for a higher EBL model. In particular, the high-EBL spectral index quoted above would locate the high-energy peak of the SED of 3C 279 at TeV energies, which would lead to even more unrealistic parameter choices for the leptonic models considered in the following section. We will therefore restrict our more detailed discussion

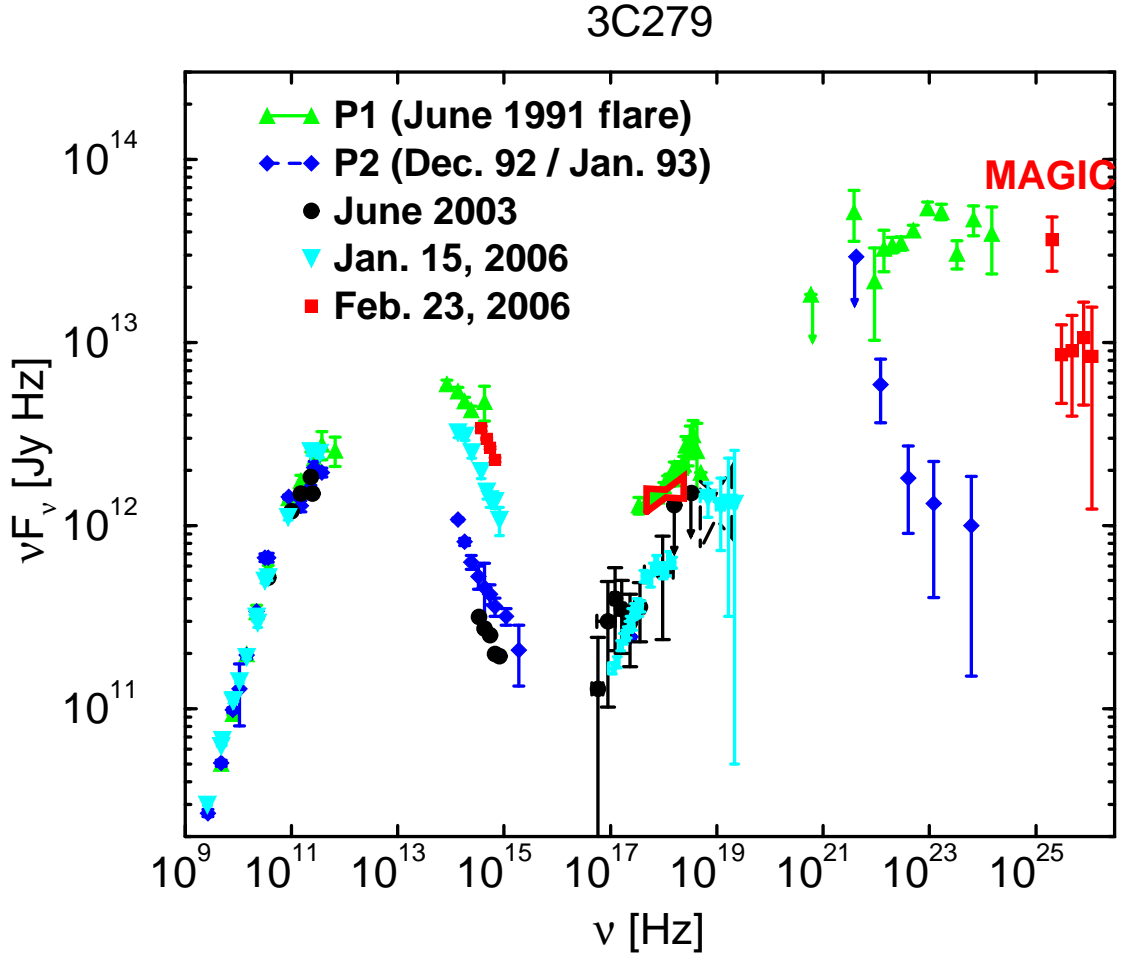


Fig. 2.— Compilation of broadband spectral energy distributions of 3C279, including the day of the MAGIC VHE detection, February 23, 2006. Data for P1 and P2 are from Hartman et al. (2001a), 2003 data are from Collmar et al. (2004), and 2006 data are from Collmar et al. (2007) and Böttcher et al. (2007b).

to the VHE spectrum corrected by the low EBL model. The optical spectrum, while clearly in an elevated state, shows about the same, steep spectral index  $\alpha_{\text{opt}} \sim 1.7$  as during lower optical flux states, indicating an underlying nonthermal electron spectral index of  $p = 4.4$ .

The slopes of the radio and optical spectra indicate that the synchrotron peak was in the usual range where it has been observed in many previous observing campaigns, i.e., in the infrared regime, around  $\nu_{\text{sy}} \sim 5 \times 10^{13}$  Hz, corresponding to a dimensionless photon energy  $\epsilon_{\text{sy}} \equiv h\nu_{\text{sy}}/(m_e c^2) \sim 4 \times 10^{-7}$ . This is consistent with the location of the synchrotron peak in a compilation of simultaneous multiwavelength data in mid-2006, shown by Marscher (2008), which included infrared coverage by the *Spitzer Space Telescope*. For the purpose of a quantitative analysis, the synchrotron peak flux may be estimated to be of the order of  $\nu F_{\nu}^{\text{sy}} \sim 10^{13}$  Jy Hz. Equally, the X-ray spectrum shows a quite typical shape as observed in previous high states of 3C 279, in particular the P1 SED shown in Figs. 2 and 4. This suggests that the X-ray – GeV  $\gamma$ -ray spectrum is similar to previously observed high states during the EGRET era.

If a one-zone leptonic jet model (as discussed in the following section) applies, the VHE spectrum is expected to be at least as steep as the optical (synchrotron) flux. The spectral indices are expected to be similar if the  $\gamma$ -ray emission is produced by Compton scattering in the Thomson regime. If Klein-Nishina effects are important in the production of VHE  $\gamma$ -rays, the resulting VHE spectrum would be even steeper than the synchrotron spectrum. As already indicated above, this would be in direct conflict with the observed relatively hard intrinsic VHE spectrum, even when corrected with a low EBL model. Therefore, in order not to predict a GeV  $\gamma$ -ray flux greatly in excess of any archival EGRET flux, it is reasonable to assume a  $\gamma$ -ray peak at  $\nu_{\gamma} \sim 10^{24} - 10^{25}$  Hz, corresponding to  $\epsilon_{\gamma} \sim 10^5$ . The  $\gamma$ -ray peak flux is then  $\nu F_{\nu}^{\gamma} \sim 5 \times 10^{13}$  Jy Hz. Previous modeling works of the SEDs of 3C 279 placed the peak of the high-energy component typically at frequencies around  $\nu_{\gamma} \sim 10^{23}$  Hz, i.e., about 1 – 2 orders of magnitude lower than our new estimate, taking the MAGIC results into account. It is this shift of the inferred high-energy peak which will lead to quite dramatically different model implications for both leptonic and hadronic models compared to previous modeling efforts.

From the spectral upturn in the UV in the P2-spectrum in Fig. 2, we can estimate a thermal (external) photon source with a luminosity of  $L_D \sim 2 \times 10^{45}$  erg s $^{-1}$ , peaking at  $\nu_D \sim 10^{15}$  Hz ( $\epsilon_D \sim 10^{-5}$ ).

### 3. Implications for Leptonic Jet Models

In this section, we consider whether a one-zone leptonic blazar jet model can account for the February 23, 2006, SED of 3C279. We consider a scenario in which a nonthermal population of ultrarelativistic electrons produces, at the same time, the synchrotron emission from radio through UV and the  $\gamma$ -ray emission via Compton scattering of soft photons off the relativistic electrons. In general, we will assume that electrons are accelerated into a power-law distribution in electron energy,  $Q(\gamma) = Q_0 \gamma^{-q}$ , in the range  $\gamma_1 \leq \gamma \leq \gamma_2$ . The emission region has a radius  $R_B \equiv 10^{16} R_{16}$  cm. We define an escape time scale parameter  $\eta_{\text{esc}}$  such that the escape time scale for relativistic electrons is  $\tau_{\text{esc}} \equiv \eta_{\text{esc}} R_B / c$ . The interplay between radiative cooling and escape leads to the development of a spectral break in the electron spectrum at a Lorentz factor  $\gamma_b$ , where the radiative cooling time scale equals the escape time scale. If the primarily injected electron distribution has a low-energy cutoff below the break Lorentz factor  $\gamma_b$  (the slow cooling regime), the spectral index of the electron distribution at  $\gamma < \gamma_b$  is  $p = q$ , while above it the spectrum is steepened to  $p = q + 1$ . However, given the steep spectral index of the optical spectrum, implying  $p = 4.4$  in the electron energy range synchrotron-radiating in the optical regime, a spectral break from  $p = 3.4$  to  $p = 4.4$  would not produce a peak in the  $\nu F_\nu$  spectrum at the characteristic synchrotron frequency corresponding to  $\gamma_b$ . Therefore, it is more likely that the injected electron distribution has a high low-energy cutoff at  $\gamma_1 > \gamma_b$ . In this case, particles at energies  $\gamma < \gamma_1$  result only from radiative cooling from higher energies, resulting in an electron spectrum with a spectral index  $p = 2$  in the range  $\gamma_b \leq \gamma \leq \gamma_1$ , while above  $\gamma_1$ , we have  $p = q + 1$ , as in the slow cooling case.

#### 3.1. SSC model

In the past, VHE emission has only been observed in high-frequency peaked BL Lac objects. In that case, a model interpreting the  $\gamma$ -ray emission as synchrotron self-Compton (SSC) emission has proven to be very successful, although recent observations of rapid variability on time scales of a few minutes (Aharonian et al. (2007) for PKS 2155-304, and Albert et al. (2007) for Mrk 501) are posing serious challenges to this interpretation (e.g. Finke, Dermer & Böttcher 2008), and the VHE emission of the intermediate BL Lac object W Comae, recently detected by VERITAS (Acciari et al. 2008) is more plausibly explained by Comptonization of an external radiation field. We point out that previous modeling efforts on 3C279, prior to the MAGIC detection, have concluded that an EC component is strongly preferred to explain the GeV  $\gamma$ -ray detection (Hartman et al. 2001a; Bednarek 1998; Sikora et al. 2001; Moderski et al. 2003). However, since the MAGIC points provide



a yet unexplored new constraint on blazar models for 3C279, it is worthwhile to revisit the SSC hypothesis in this paper.

Given the synchrotron origin of the low-frequency peak at  $\epsilon_{\text{sy}} \sim 4 \times 10^{-7}$  and the SSC origin of the  $\gamma$ -ray peak at  $\epsilon_\gamma \sim 10^5$ , the Lorentz factor of electrons  $\gamma_p$  radiating at the synchrotron and SSC peaks, can be estimated from

$$\gamma_p = \sqrt{\frac{\epsilon_\gamma}{\epsilon_{\text{sy}}}} \sim 1.6 \times 10^5. \quad (1)$$

At the same time, the synchrotron peak frequency is given by

$$\nu_{\text{sy}} = 4.2 \times 10^6 \gamma_p^2 B_G D / (1 + z) \text{ Hz} \quad (2)$$

where  $B_G$  is the (co-moving) magnetic field in Gauss, and  $D \equiv 10 D_1 = (\Gamma[1 - \beta_\Gamma \cos \theta_{\text{obs}}])^{-1}$  is the Doppler enhancement factor. This yields an estimate of the magnetic field and the Doppler factor of

$$B_G D_1 \sim 7 \times 10^{-5}. \quad (3)$$

This indicates that such a scenario would imply unrealistically low magnetic fields compared to standard values of  $\sim 1$  G found from SED modeling of 3C279 in other states, as well as other blazar-type quasars. Even other known TeV blazars, whose SEDs can usually be well represented with SSC models, typically require magnetic fields of  $B \gtrsim 0.1$  G, several orders of magnitude above the estimate found here for 3C279. We therefore conclude that a one-zone SSC model for the SED of 3C279 on February 23, 2006, including the VHE  $\gamma$ -ray emission is very problematic.

### 3.2. External Compton

The leptonic external-Compton scenario is based on the assumption that photons from an external, quasi-isotropic radiation field with dimensionless photon energy  $\epsilon_s$  are Compton-upscattered to the observed  $\gamma$ -ray photon energies. As mentioned earlier, if Klein-Nishina effects become important in the production of the VHE emission, the resulting VHE  $\gamma$ -ray spectrum would be even steeper than the observed synchrotron spectrum, in contradiction with the observed VHE spectrum, even when corrected for the lowest plausible level of EBL  $\gamma\gamma$  absorption. We therefore consider here only the possibility that the VHE  $\gamma$ -rays in a leptonic scenario are produced by Thomson scattering. Soft photons can be upscattered

effectively in the Thomson regime at most up to energies  $\epsilon_\gamma = 1/\epsilon_s$ . This indicates that a photon field with a characteristic photon energy of the accretion disk field at  $\epsilon_D \sim 10^{-5}$  can effectively serve as the seed photon field for upscattering to the observed  $> 100$  GeV  $\gamma$ -rays. We assume that a fraction  $\tau_{BLR} \equiv 10^{-1}\tau_{-1}$  of the accretion disk radiation is reprocessed in the broad line region, which is located at an average distance  $R_{BLR} \equiv 0.1 R_{BLR,-1}$  pc from the central engine. HST near-UV spectroscopy (Pian et al. 2005) indicates that the total luminosity of the BLR in 3C279 is  $L_{BLR} \sim \tau_{BLR} L_D \sim 2 \times 10^{44}$  erg/s, motivating the above scaling in terms of  $\tau_{-1}$ . In the co-moving frame, the external photons will thus have a characteristic energy of  $\epsilon'_s = \Gamma \epsilon_s$ . In addition to Eq. (2), we now have an independent estimate for  $\gamma_p$ , namely

$$\gamma_p = \sqrt{\frac{\epsilon_\gamma}{\Gamma^2 \epsilon_D}} \sim 10^4 \Gamma_1^{-1}. \quad (4)$$

We can use Eq. (2) to obtain an estimate for the magnetic field:

$$B_G = 1.8 \times 10^{-2} \Gamma_1^2 D_1^{-1}. \quad (5)$$

The energy density of external photons in the co-moving frame can be expressed as

$$u'_{\text{ext}} \sim \frac{L_D \tau_{BLR} \Gamma^2}{4\pi R_{BLR}^2 c}. \quad (6)$$

From the  $\gamma$ -ray dominance,  $L_\gamma/L_{\text{sy}} \sim u'_{\text{ext}}/u'_B \sim 5$ , we can then obtain an independent estimate of the magnetic field of

$$B_G = 1.0 \tau_{-1}^{1/2} \Gamma_1 R_{BLR,-1}^{-1}. \quad (7)$$

Combining the magnetic field estimates (5) and (7), we find

$$R_{BLR,-1} = 57 \tau_{-1}^{1/2} \quad (8)$$

which is in drastic contrast to the estimate of Pian et al. (2005) of  $R_{BLR} \sim 3 \times 10^{-2}$  pc.

Considering the peak level of the synchrotron flux, we can use Eq. (8) of Böttcher et al. (2003) to relate the magnetic field in the emission region with the equipartition fraction  $e_B \equiv u'_B/u'_e$ , i.e., the ratio of co-moving energy densities in the magnetic field and the nonrelativistic electron population:

$$B_{e_B} = 1.25 D_1^{-1} \left( \frac{d_{27}^4 f_{-10}^2 e_B^2}{[1+z]^4 \epsilon_{\text{sy},-6} R_{16}^6 [p-2]} \right)^{1/7}. \quad (9)$$

Setting this equal to the magnetic-field estimate (5) yields

$$e_B = 9.7 \times 10^{-9} R_{16}^3 \Gamma_1^7. \quad (10)$$

Consequently, if we choose a conventional value of the Lorentz factor  $\Gamma \sim 15$ , we find an uncomfortably low magnetic field of  $B \sim 0.03$  G, corresponding to  $e_B \sim 1.7 \times 10^{-7} R_{16}^3$ , i.e., a far sub-equipartition magnetic field. Such a situation would make jet confinement very problematic, and is in contradiction with model results for 3C279 in other observing epochs and for other quasar-type blazars in general, where magnetic fields of typically  $B \sim 1$  – a few G are inferred, in approximate equipartition with the relativistic electron population.

Alternatively, forcing the system to attain approximate equipartition would require us to assume an uncomfortably high Lorentz factor of  $\Gamma \sim 140 R_{16}^{-3/7}$ . This choice of a bulk Lorentz (and Doppler) factor would imply  $B \sim 0.25$  G, and a low-energy cut-off of the injected electron population at  $\gamma_1 = \gamma_p \sim 710 R_{16}^{3/7}$ . Apart from the fact that this is an order of magnitude larger than bulk Lorentz factors inferred from superluminal motion, it would require an implausibly close alignment of the jet with our line of sight,  $\theta_{\text{obs}} \sim 0.4^\circ$ . We note that the magnetic-field estimate of Eq. (5) carries a proportionality  $B \propto (\epsilon_s/\epsilon_\gamma)$ . Since our choice of  $\epsilon_s \sim 10^{-5}$  is already close to the largest possible value to allow Thomson scattering to TeV  $\gamma$ -rays, the assumption of a different soft photon source (necessarily with a smaller  $\epsilon_s$ ) would worsen the problem of the unusually small inferred magnetic field.

It has been noted by several authors that the  $\gamma\gamma$  absorption of VHE  $\gamma$ -ray photons by the radiation field of the BLR may present another problem for a model of VHE  $\gamma$ -ray emission inside the BLR of luminous quasars in general (e.g. Donea & Protheroe 2003; Reimer 2007) and 3C279 in particular (Liu et al. 2008; Sitarek & Bednarek 2008). We therefore need to investigate the effects of  $\gamma\gamma$  absorption in the BLR radiation field for the parameters we inferred above. In Böttcher & Dermer (1995), the time-dependent  $\gamma\gamma$  absorption signatures of an accretion disk flare (reflected by BLR clouds) on VHE  $\gamma$ -ray emission were investigated. We have modified their approach for our purposes, adopting non-variable accretion-disk emission. The standard optically-thick accretion-disk spectrum is approximated by a spectral shape  $F_\epsilon \propto \epsilon^{1/3} e^{-\epsilon/\Theta_D}$ , where  $\Theta_D \sim 10^{-5}$  is the dimensionless inner disk temperature,  $\Theta_D = kT_{\text{D,in}}/(m_e c^2)$ . Fig. 3 illustrates the dependence of the  $\gamma\gamma$  absorption depth as a function of the dimensionless photon energy  $\epsilon$  and location of the  $\gamma$ -ray production site. Our results confirm the findings of Liu et al. (2008): With standard values of the BLR parameters,  $\tau_{\text{BLR}} \sim 0.1$ ,  $R_{\text{BLR}} \sim 0.03$  pc, as inferred by Pian et al. (2005), VHE  $\gamma$ -rays produced within

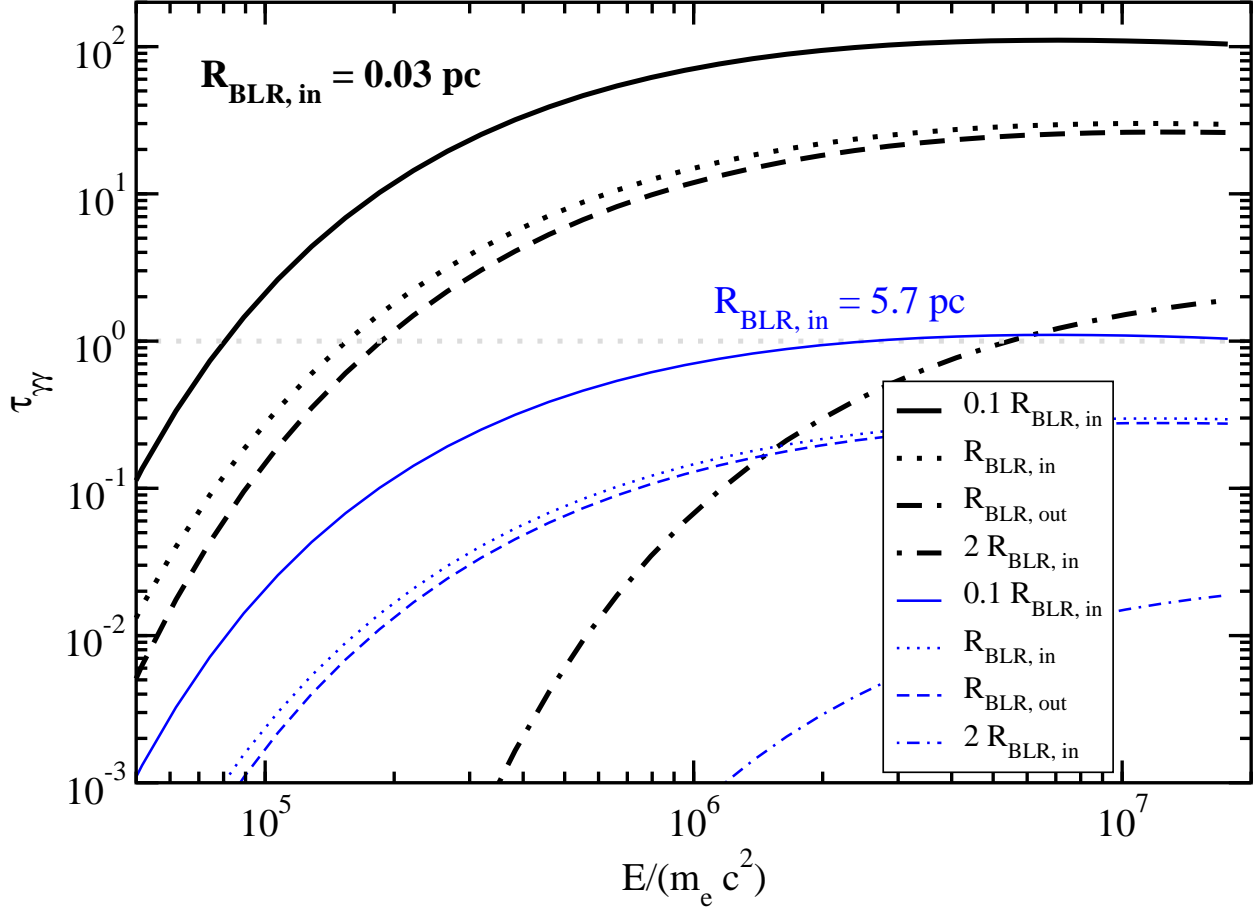


Fig. 3.— Opacity for VHE  $\gamma$ -ray photons due to  $\gamma\gamma$  absorption on the BLR radiation field. The labels denote the location of the  $\gamma$ -ray emitting region. Other parameters:  $L_D = 2 \times 10^{45}$  erg/s,  $\Theta_D = 10^{-5}$ ,  $\tau_{\text{BLR}} = 0.1$ . Heavy (black) curves refer to the value of  $R_{\text{BLR},\text{in}} = 0.03$  pc as inferred by Pian et al. (2005) with the outer edge of the BLR,  $R_{\text{BLR},\text{out}} = 0.031$  pc; light (blue) curves refer to  $R_{\text{BLR},\text{in}} = 5.7$  pc as inferred from Eq. 8 and  $R_{\text{BLR},\text{out}} = 5.8$  pc. The photon energy  $E$  is in the stationary AGN rest frame.

the BLR of 3C279 suffer severe  $\gamma\gamma$  absorption by the same photon field that would serve as seed photon field for Compton scattering in a leptonic model. For the extreme parameters of  $\Gamma \sim 140$ , requiring  $R_{\text{BLR}} \sim 5.7$  pc,  $\tau_{\text{BLR}} \sim 0.1$ ,  $\gamma\gamma$  absorption would hardly be a problem even out to multi-TeV  $\gamma$ -ray energies, if the  $\gamma$ -rays are produced close to the inner boundary of the BLR. Any level of  $\gamma\gamma$  absorption in the BLR radiation field would imply an even higher level of intrinsic VHE  $\gamma$ -ray emission and therefore make the requirements for jet parameters in a one-zone leptonic model even more extreme.

The red, solid curve in Fig. 4 shows a leptonic model calculation with parameters similar to the quasi-equipartition case outlined above. We used an equilibrium version of the time-dependent SSC + EC model of Böttcher & Chiang (2002). While the optical (synchrotron) spectrum and the level of the VHE  $\gamma$ -ray flux can be reproduced reasonably well, it is obvious that the X-ray flux is grossly underproduced. This is a consequence of the required, rather large low-energy cutoff at  $\gamma_1 \sim 700$ . The choice of a substantially lower  $\gamma_1$  would extend both the synchrotron and the  $\gamma$ -ray spectra towards lower frequencies along the slopes of the optical and VHE  $\gamma$ -ray spectra and would therefore produce unreasonably large infrared and MeV – GeV  $\gamma$ -ray fluxes. In addition, it would require a larger jet power and therefore drive the system further out of equipartition (towards far sub-equipartition magnetic fields). Also, even though most of the  $> 100$  GeV flux is produced by Compton scattering in the Thomson regime, the resulting VHE  $\gamma$ -ray spectrum appears to be steeper than the observed one, even with correction for the low EBL level according to Primack et al. (2005).

We therefore conclude that both the SSC and the external-Compton scenario for a one-zone, homogeneous jet model face severe problems representing the simultaneous SED of 3C279 on February 23, 2006, including the VHE  $\gamma$ -ray emission.

As noted earlier, the VHE  $\gamma$ -ray flare was not accompanied by any remarkable optical variability. This may be another hint that in 3C279 the optical and VHE  $\gamma$ -ray fluxes may be produced in separate emission regions. However, the calculation of the  $\gamma\gamma$  opacity above indicates that even an inhomogeneous leptonic jet model would face severe problems in an external-Compton scenario. The dashed red curve in Fig. 4 indicates that an SSC model can successfully reproduce the X-ray – VHE  $\gamma$ -ray spectrum with reasonable parameters, but fails to reproduce the optical spectrum. This may indicate support for a multi-zone leptonic model. This would require that the VHE  $\gamma$ -ray emission is produced far outside the BLR, possibly in an internal shock scenario (Spada et al. 2001; Sokolov, Marscher & McHardy 2004). This is indicated both by the  $\gamma\gamma$  opacity argument as well as the low required magnetic field for the SSC fit presented in Fig. 4. Such a model would imply that the X-ray emission is produced by low-energy electrons which have undergone substantial radiative cooling. One would therefore predict a delay of X-rays with respect to  $\gamma$ -rays on the order

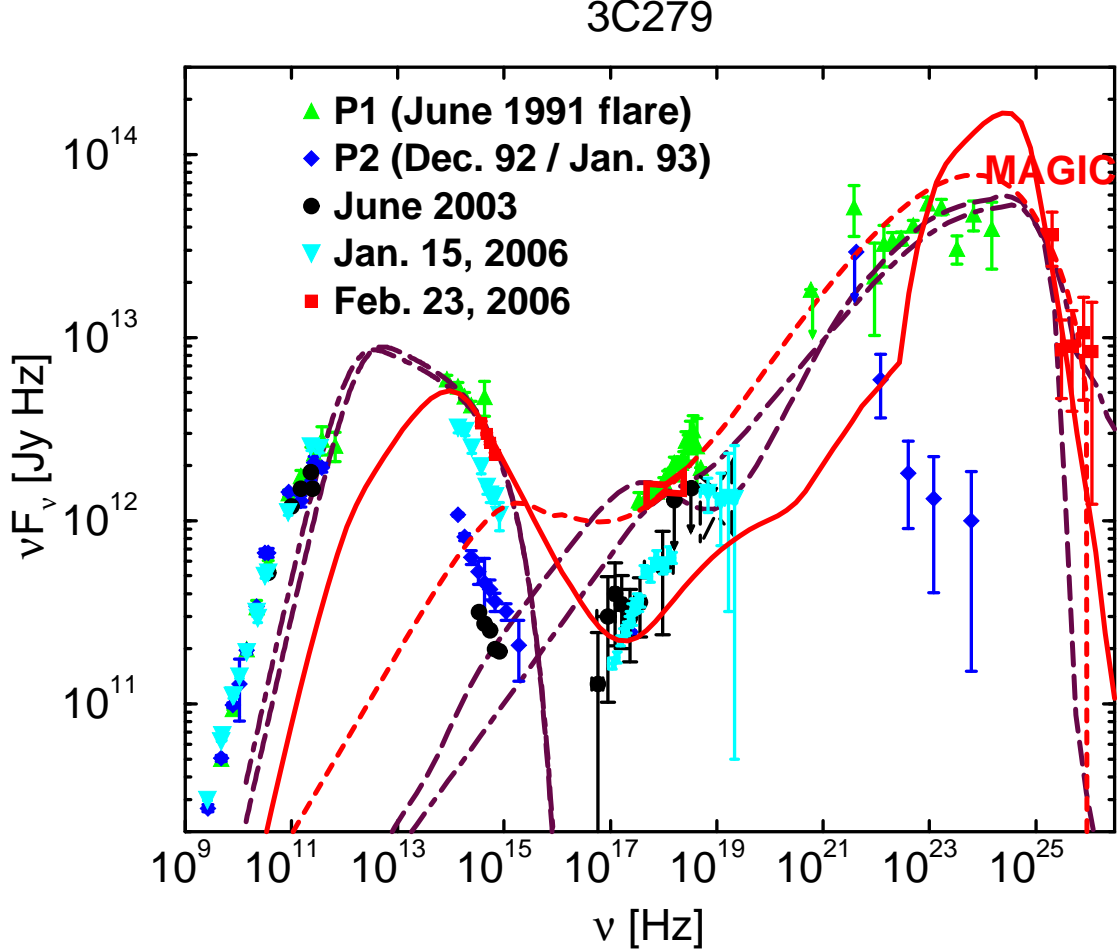


Fig. 4.— Spectral fits to the SED of 3C279 on February 23, 2006: (solid [red]) using a leptonic External-Compton model with parameters similar to those derived in §3.2; (short-dashed [red]) leptonic SSC model fit only to the X-ray –  $\gamma$ -ray spectrum. Relevant parameters:  $\gamma_1 = 10^4$ ,  $\gamma_2 = 10^6$ ,  $q = 2.3$ ,  $L_{j,e} = 2.2 \times 10^{47}$  erg s $^{-1}$ ,  $\eta_{\text{esc}} = 80$ ,  $R_B = 6 \times 10^{15}$  cm,  $\Gamma = D = 20$ ,  $B = 0.2$  G; (dot-dashed [maroon]) fit with the hadronic synchrotron-proton blazar model with internal (synchrotron) photons only as targets for  $p\gamma$  pion production, and (long-dashed [maroon]) with synchrotron + external (BLR) photons as targets for  $p\gamma$  pion production. See table 1 for parameters.

of the electron cooling time scale,

$$\tau_{\text{cool,SSC}}^{\text{obs}} \sim \frac{m_e c^2}{D (4/3) c \sigma_T u'_B (L_{\text{SSC}}/L_{\text{sy}}) \gamma}. \quad (11)$$

Using the value of  $B = 0.2$  G used for the model shown in Fig. 4, and scaling the electron energy  $\gamma \equiv 10^3 \gamma_3$ , we find the expected  $\gamma$ -ray vs. X-ray delay as  $\tau \sim 27 \gamma_3^{-1}$  hr. We note, however, that an intensive search for inter-band time delays between optical, X-ray and  $\gamma$ -ray emission of 3C279 during the EGRET era by Hartman et al. (2001b) did not find any evidence for systematic  $\gamma$ -ray vs. X-ray delays.

#### 4. Hadronic Models

If relativistic protons at energies above the threshold for  $p\gamma$  pion production are present in the jet of 3C 279, hadronic interactions must be considered in blazar emission models. For the present modeling we use the hadronic Synchrotron-Proton Blazar (SPB) model of Mücke & Protheroe (2001); Mücke et al. (2003). In its original version, this model was best suited for X-ray selected BL Lac objects with very weak or absent external radiation fields. However, the quasar 3C 279 is known to have strong accretion disk and BLR line emission (see §3.2). We therefore extend the (one-zone) SPB model to account also for target photon fields external to the jet.

Relativistic electrons (e) and protons (p) with a power law index  $q_e = q_p$  are injected instantaneously into a spherical emission region, or blob, which is moving with relativistic velocity along the jet axis. In the strongly magnetized (with field strength  $B = \text{const.}$ ) blob, the primary electrons lose their energy predominantly through the synchrotron channel. The resulting synchrotron radiation generally dominates the low energy component of the blazar SED, and serves as target photon field for proton-photon interactions and pair (synchrotron) cascading. In our extension of the SPB model we add the photon field from the BLR, simplified as an isotropic distribution in the jet frame (see Reimer, Böttcher & Postnikov 2005, for a discussion of this approximation) as an additional target for particle-photon interactions and cascading. We properly take into account the Doppler boost of the average photon energy and photon energy density of the external photon field. In the present work we use the approximation advocated by Tavecchio & Ghisellini (2008) for the BLR radiation field: In the co-moving jet frame a blackbody spectrum with temperature  $T' \propto \Gamma \nu_{\text{Ly}\alpha}$  ( $\nu_{\text{Ly}\alpha}$  the Ly $\alpha$  line frequency) is used to approximate the boosted BLR emission from the stationary AGN to the blob frame. Local absorption of  $\gamma$ -rays (Reimer 2007) external to the emission region is taken into account as well. The injected relativistic protons suffer energy losses from

photomeson production, Bethe-Heitler pair production, synchrotron radiation and adiabatic expansion. Charged particles produced as secondaries in the photomeson production channel may suffer synchrotron losses as well prior to their decay. This is particularly relevant for charged pions and muons (henceforth named  $\mu$ -synchrotron radiation). All high energy photons may initiate pair cascades, which redistributes a fraction of the photon power from high to lower energies where the photons can eventually escape the emission region.

In the framework of the hadronic SPB model the injection electron spectrum is primarily constrained by the optical and radio data. For  $q_e = 2.1 - 2.2$  the primary electron synchrotron spectrum above the synchrotron self-absorption turnover shows a rather flat spectrum from the injected particle spectrum, modified by synchrotron losses, followed by a steep tail due to the cutoff of the electron distribution at particle Lorentz factors  $\sim 10^3$ . The high energy component of the SED of 3C 279 is constrained by the RXTE and MAGIC data. In the SPB model the RXTE data can in general be explained by either proton synchrotron radiation, or a reprocessed/cascade component. The former suggests, however, extremely long loss time scales (of order years for typical field strengths and Doppler factors in the SPB model), which is difficult to reconcile with the observed day-scale variability. We therefore concentrate on the second option of reprocessed radiation dominating the X-ray band. This picture is also strengthened by the softness of the X-ray spectrum, which may indicate the appearance of reprocessed (through  $\gamma\gamma$  pair production) radiation in this energy range.

The left panel in Fig. 5 shows a typical model fit to the SED of 3C 279 of February 23, 2006, for the case of a negligible external photon field at the location of the  $\gamma$ -ray emission region. While radiation in the  $\gamma$ -ray band is dominated by proton and  $\mu$  synchrotron emission, reprocessed proton synchrotron radiation determines the photon emission in the X-ray band. For the required bulk Doppler factors  $D = 10 - 14$ , and assuming a size of the emission region of order  $\sim 10^{16}$  cm, the energy density of the internal jet target photon field amounts to  $u'_{\text{sy}} \sim \text{a few } 10^{10} - 10^{11} \text{ eV cm}^{-3}$ . With these values, a delay between the TeV and X-ray band of a few days may be explainable. The strong magnetic field strengths of 40 – 60 G imply losses due to proton synchrotron radiation in the TeV band on hour time scales. Interestingly, all models representing the simultaneous data of February 23, 2006, reasonably well require a cutoff of the injected proton spectrum at a few  $10^9$  GeV, which is significantly lower than what is needed for HBL-like TeV-blazars. The injected proton energy density  $u'_p$  is of the order  $10^2 - 10^3 \text{ erg cm}^{-3}$ , not too far from the equipartition value  $u'_{\text{p,equi}}$  (here  $u'_p \approx 2 - 17 u'_{\text{p,equi}}$ ), and a total jet luminosity (as measured in the galaxy rest frame) of order  $10^{48-49} \text{ erg s}^{-1}$ .

If the gamma-ray emission region is rather close to the BLR, the external photon field has to be taken into account as an additional target for particle-photon interactions and pair



Table 1. Parameters for the hadronic synchrotron-proton blazar model fits to 3C279 (Figs. 4 and 5) for (2nd col.) internal synchrotron photons only, and (3rd col.) internal synchrotron + external (BLR) photons as targets for  $p\gamma$  pion production.

Parameter	symbol	SPB (sy.)	SPB (sy. + ext.)
Jet power	$L_j$ [ $\text{erg s}^{-1}$ ]	$1 \times 10^{49}$	$6.6 \times 10^{48}$
Doppler factor	$D$	12	12
Blob radius	$R_b$	$3 \times 10^{16}$ cm	$3 \times 10^{16}$ cm
Maximum proton energy	$E_{p,\text{max}}$	$5 \times 10^9$ GeV	$4.5 \times 10^9$ GeV
Magnetic field	$B$	40 G	60 G
Particle spectral index	$q_p = q_e$	2.2	2.2
Proton energy density	$u_p$ [ $\text{erg cm}^{-3}$ ]	$1.2 \times 10^3$	540
Electron/proton density ratio	$n_e/n_p$	$2 \times 10^{-3}$	$3 \times 10^{-3}$
Temperature of BLR emission	$kT_{\text{BLR}}$	—	3 eV
BLR photon energy density	$u_{\text{BLR}}$	—	$10^{-3}$ $\text{ergs cm}^{-3}$
BLR radius	$R_{\text{in,BLR}}$	—	0.1 pc
Location of emission region	$R_{\text{em}}$	—	0.18 pc

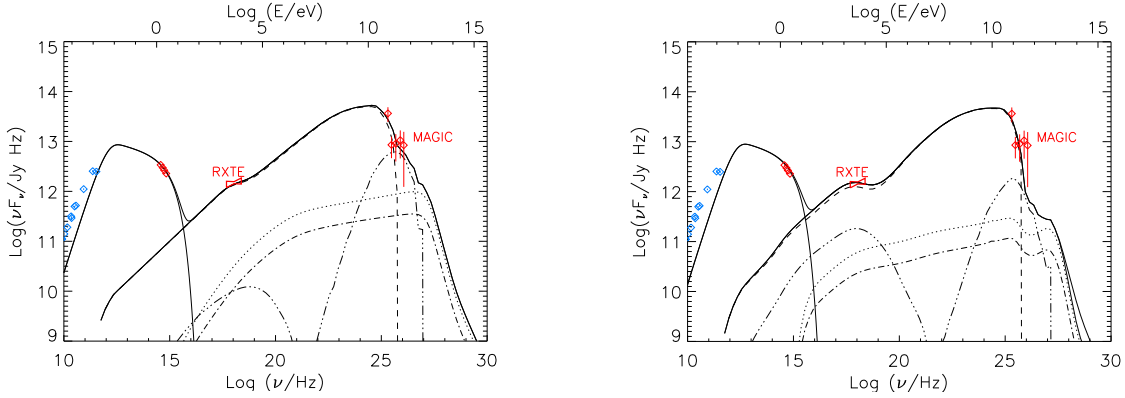


Fig. 5.— Hadronic fits to the SED of 3C279. Left: Pure synchrotron-proton blazar model with only intrinsic synchrotron photons as targets for  $p\gamma$  pion production; right: synchrotron proton blazar model including external photon field from the BLR. See table 1 for parameters. Individual radiation components are: dashed: proton synchrotron and cascade; triple-dot-dashed:  $\mu$  synchrotron and cascade; dotted:  $\pi^0$  cascade; dot-dashed:  $\pi^\pm$  cascade.

cascading. The observed line and disk luminosity of 3C 279 implies  $\tau_{BLR} \equiv L_{BLR}/L_D \approx 0.08$ . The additional target photon field in the optical/UV band leads to enhanced reprocessing in the hadronic model, further softening the spectrum in the X-ray band. Signatures of  $\gamma$ -ray absorption due to the additional narrow-banded external photon field are clearly visible in the MAGIC energy range. The right panel in Fig. 5 shows an example of a model fit representing again the February 23, 2006, data. Proton synchrotron radiation dominates in the  $\gamma$ -ray band. The reprocessed component is more pronounced here than for the case of internal target photon fields only, which yields a more appropriate description of a potentially steep X-ray spectrum.  $\gamma\gamma$  absorption of VHE  $\gamma$ -ray photons in the external radiation field inevitably leads to a steepening of the VHE  $\gamma$ -ray spectrum. The fit shown in Fig. 5b presents an acceptable representation of the MAGIC spectrum. Should a higher EBL level imply a harder intrinsic VHE  $\gamma$ -ray spectrum, this fit could be modified by choosing a lower energy density of the external radiation. Parameter values for hadronic model fits are given in Table 1. For the fit with external photons, the injected proton energy densities are at most a factor 4 above the equipartition value and the required total jet luminosity of  $\sim (1 - 7) \times 10^{48} \text{ erg s}^{-1}$  is somewhat lower than for the case of internal target photon fields only.

## 5. Summary

We have presented simultaneous optical and X-ray spectral information to the recent MAGIC detection of the quasar-type blazar 3C279 in February 2006. The source was shown to be in an elevated optical state, but showed no substantial optical variability and a rather steep optical spectrum during the MAGIC detection. The GeV – TeV flare preceded an X-ray flare by about 5 – 7 days. We have presented the simultaneous broadband (optical - X-ray - VHE  $\gamma$ -rays) SED of 3C279 and discuss its implication for one-zone leptonic jet models. We found that an SSC model is extremely problematic as it would imply unreasonably low magnetic fields. Also an external-Compton interpretation has problems with an unusually low magnetic field of  $B \sim 0.03 \text{ G}$ , implying an equipartition ratio of  $e_B \sim 10^{-8}$ . Alternatively, approximate equipartition can be achieved with a bulk Lorentz factor of  $\Gamma \sim 140 R_{16}^{-3/7}$ , which appears equally unlikely. These constraints have been inferred for a correction of the VHE spectrum for  $\gamma\gamma$  absorption by the lowest plausible EBL model and without taking into account internal  $\gamma\gamma$  absorption by photons from the accretion disk or the broad-line region. Any higher EBL level or a substantial amount of internal  $\gamma\gamma$  absorption would lead to even more extreme constraints.

We therefore conclude that a simple homogeneous, one-zone leptonic jet model has serious problems reproducing the SED of 3C279 on February 23, 2006, which includes the

recent VHE  $\gamma$ -ray detection by MAGIC. The lack of correlated optical –  $\gamma$ -ray variability suggests, instead, a multi-zone model in which the optical and  $\gamma$ -ray fluxes are produced in separate regions along the jet. We have shown that a leptonic SSC fit to the X-ray — VHE  $\gamma$ -ray spectrum alone can be achieved with parameters quite typical for quasar-type blazars.

Alternatively, the hadronic synchrotron-proton blazar model is able to provide an acceptable fit to the SED of 3C279. Both a pure synchrotron-proton blazar model (without external photons as targets for  $p\gamma$  pion production) and a model with a substantial contribution from external target photons can reproduce the observed SED up to VHE  $\gamma$ -ray energies very well. If no external photon field is included in the model, the relevant proton synchrotron energy loss time scale is of the order of years and would therefore be inconsistent with the observed day-scale variability if proton synchrotron radiation was dominant in the X-ray regime. This model therefore requires a high internal radiation energy density in order for proton-synchrotron induced cascades to dominate the X-ray emission. Alternatively, an additional target photon contribution from external sources (in particular, the BLR) is able to overcome this problem, and such a model seems to provide an appropriate fit to the observed SED of 3C279 from optical to VHE  $\gamma$ -rays. However, both versions of the hadronic synchrotron proton blazar model require a rather extreme jet power of  $L_j \sim 10^{49}$  erg s $^{-1}$ . For comparison, a multi-zone leptonic model requires a jet power in leptons alone of  $L_{j,e} \sim 2.2 \times 10^{47}$  erg s $^{-1}$ . When including an equal number of cold protons, the total jet power requirement increases to  $L_{j,tot} \sim 2.6 \times 10^{47}$  erg s $^{-1}$ .

We point out that our conclusions are based on rather incomplete frequency coverage during the MAGIC detection, and rely on the apparent similarity of the SED, at least from radio through X-rays, with previously observed high states of 3C279 during the EGRET era. Future simultaneous Fermi LAT and TeV  $\gamma$ -ray observations (with a detection at  $> 100$  GeV  $\gamma$ -rays) would provide crucial tests to our conjectures put forth in this paper.

The work of M. Böttcher and was partially supported by NASA through XMM-Newton GO grant awards NNX07AR88G and NNX08AD67G. The work of A. Marscher was funded in part by the National Science Foundation through grant AST-0406865 and by NASA through RXTE Guest Investigator grant NNX06AG86G and Astrophysical Data Analysis Program grant NNX08AJ64G.

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